FUEL BURNING RATES OF DOWNWARD VERSUS HORIZONTALLY SPREADING FIRES

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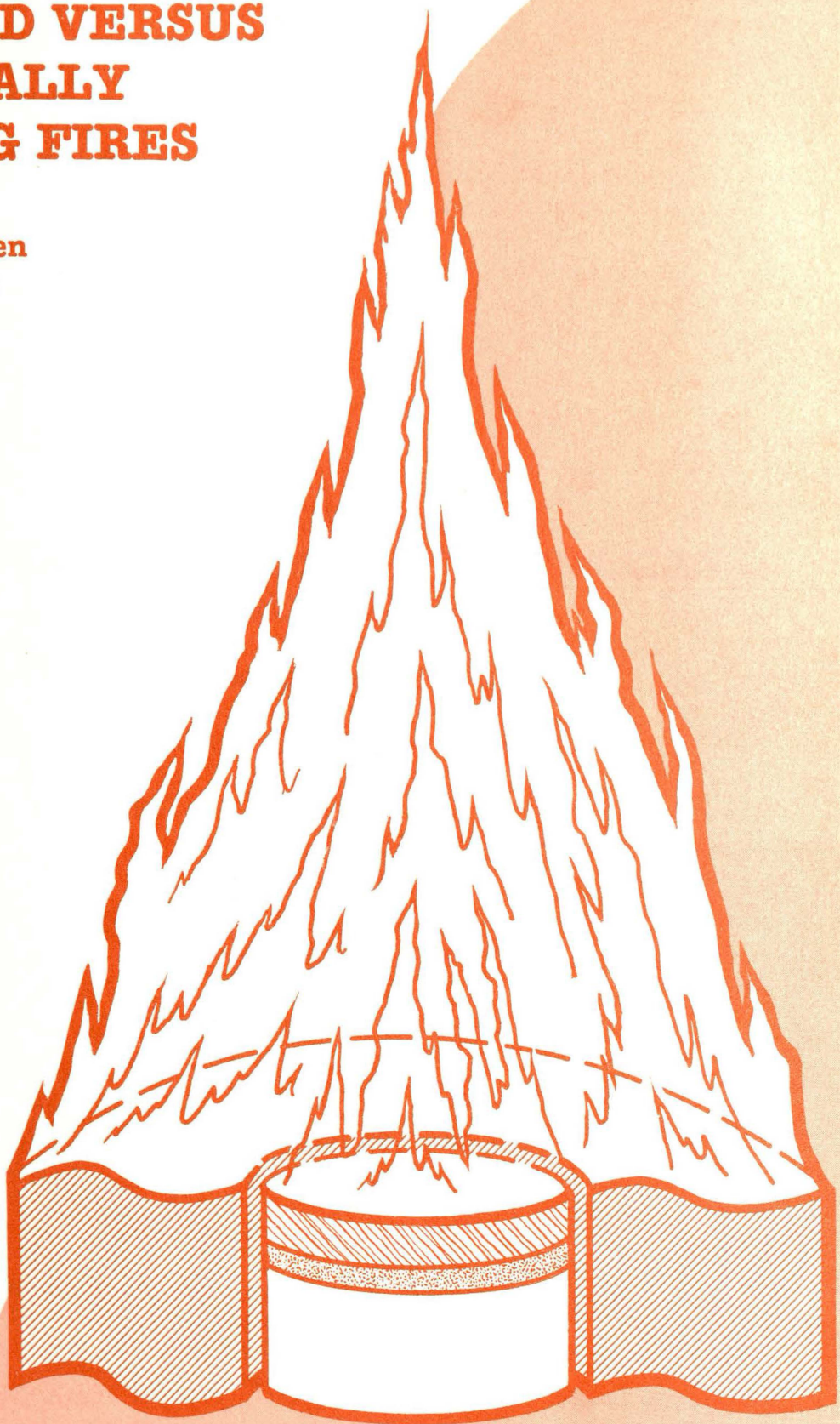

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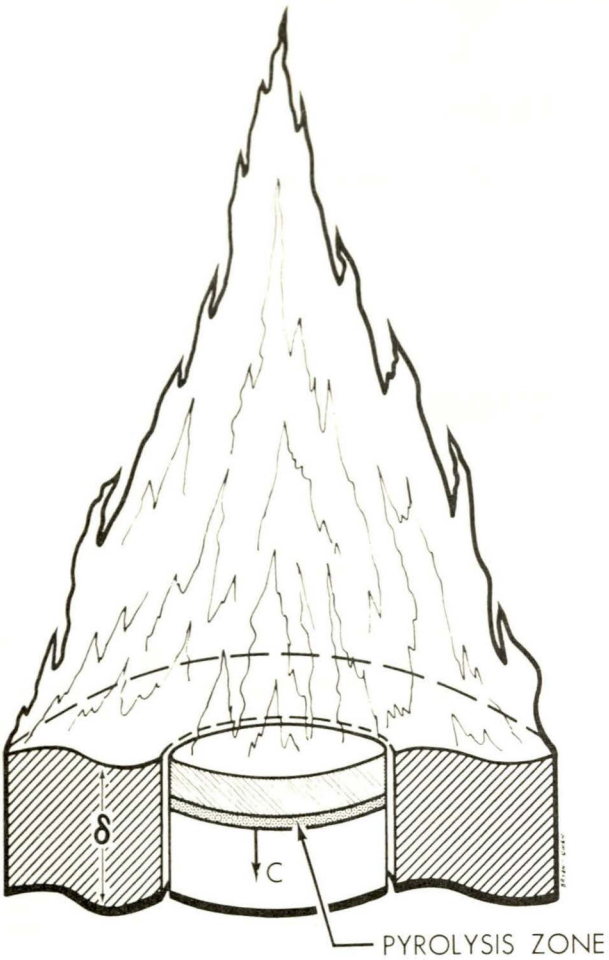

Figure 1.--A horizontal pyrolysis zone moving downward at a rate, C, through a weighed fuel basket of depth, δ. A doughnut-shaped basket surrounds the weighed basket to eliminate edge effects.

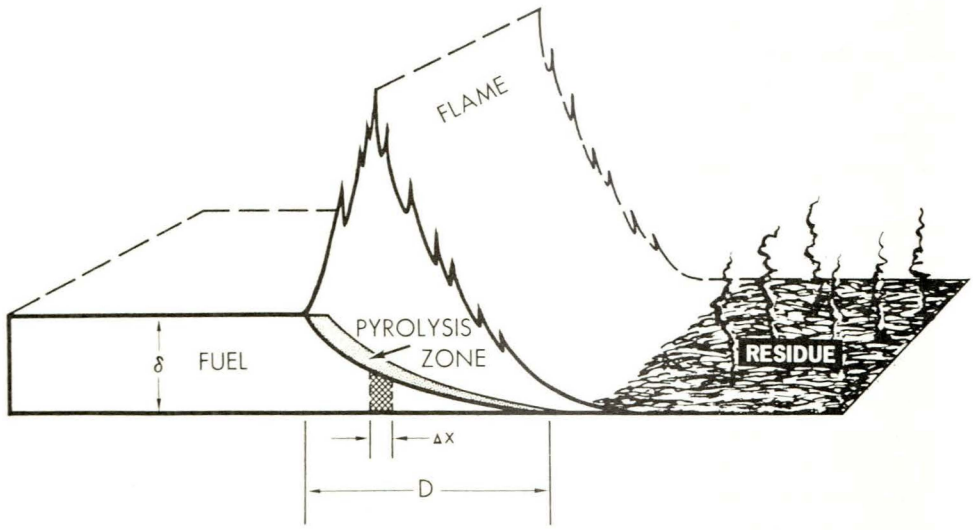

Figure 2.--A cross-sectional view of a fire spreading horizontally through a fine fuel (complete burnout). A weighed fuel slice is illustrated by Δx. The lower boundary of the pyrolysis zone is the ignition interface with the fuel.

EXPERIMENTAL PROCEDURE

The experiment was conducted in the combustion chamber of the Northern Forest Fire Laboratory. The combustion chamber is connected to an environmental conditioning facility capable of maintaining humidity within ±1.5 percent and temperature within ±33° F (±0.5° C). The entire series of experimental burns was run at 80° F (27° C) and 20 percent relative humidity, resulting in a 5 percent equilibrium moisture content for the fuel. The burns were conducted under an exhaust flue in the center of the combustion chamber 44 by 44 by 66 ft (13.4 by 13.4 by 20.1 m.)

A wire mesh basket (13 by 13 mm grid mesh size), 1 ft^2 (929 cm^2) in circular area and 0.5 ft (15.2 cm) deep was used to contain the fuel. Square cut aspen wood excelsior (*Populus tremuloides* Michx.), 0.07 cm in cross-sectional dimension (a fine fuel) was used; the same fuel was used in the original spreading fire experiment to which the burning basket results are to be compared. The particle density was 0.40 g/cm^3. Different packing ratios were obtained by changing the load while holding the depth fixed. A doughnut-shaped basket with an annular space of 0.5 ft (15.2 cm) and identical depth and packing ratio surrounded the inner basket (fig. 1) to eliminate edge effects and thus maintain a horizontal planar combustion front as the fire moves downward through the inner basket. Separation between the baskets is highly important. An annular space of one-fourth inch (0.6 cm) separating the inner and outer baskets was optimum for these tests. A larger space will result in increased burning within the open annular space deteriorating the horizontal combustion front, whereas a smaller space will result in serious disturbance to the load measurement through connecting bridges occasioned by heat warping the adjacent wire mesh walls of the baskets.

A string presoaked in xylene, a highly flammable fluid, was laid back and fourth over the upper surface of the fuel to insure uniform ignition. The load was monitored by a load cell transducer located below the inner fuel basket and insulated from the heat by baffles that also prevented airflow through the annular space between the center basket and the outer ring of fuel.

RESULTS

Figure 3 is a representative set of fuel load histories for each packing ratio, β. The load-loss rate was obtained simultaneously with the load history by electronically differentiating the signal from the load cell transducer. The differentiated signal was also used to determine the first indication of weight loss for the curves in figure 3 because of its greater sensitivity to changes in the load. Except for $\beta = 0.065$, each curve has an initial negligible load loss.

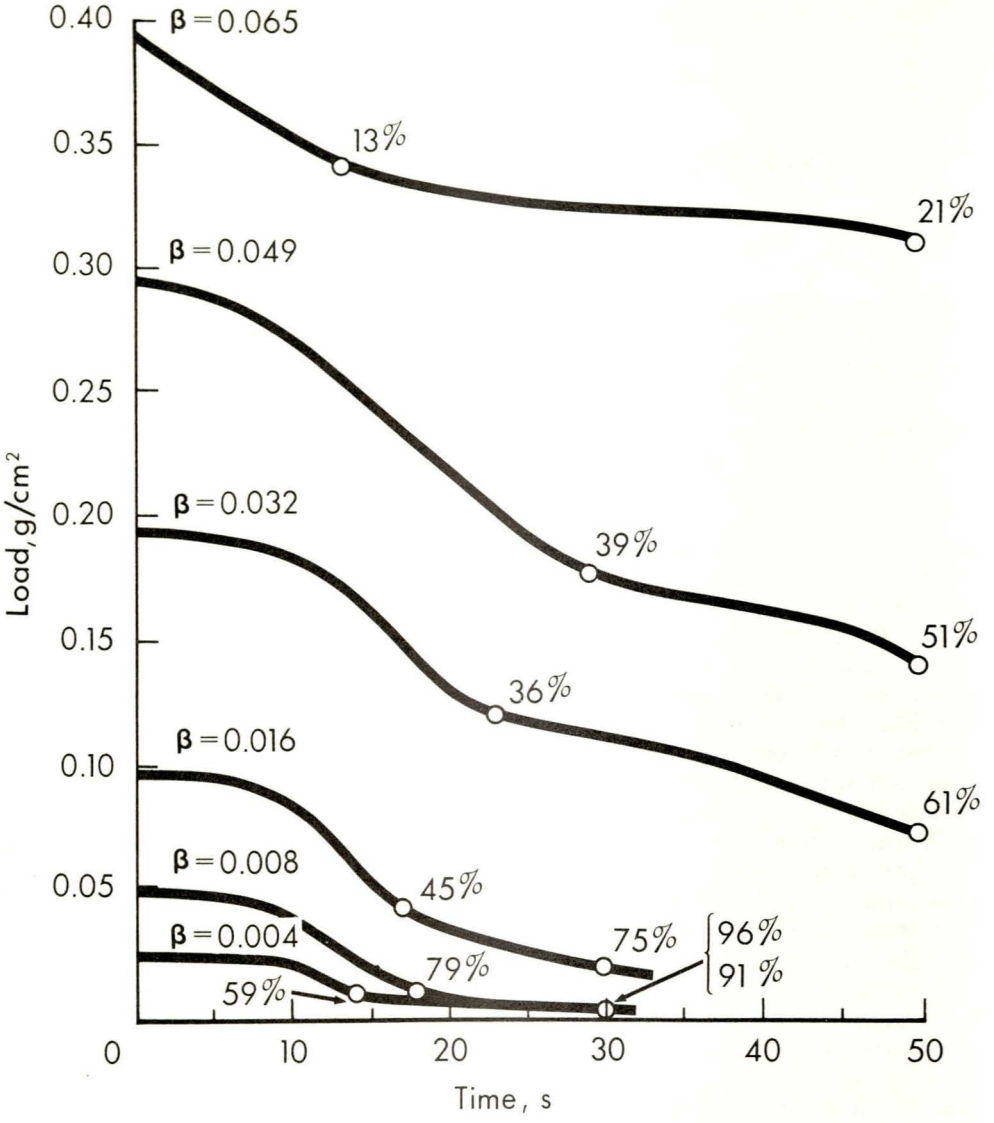

Figure 3.--Typical load histories of burning fuel baskets at six different packing ratios. The percent load loss through combustion is indicated at the end of the first major period of fuel consumption and at 30 seconds for β = 0.004 to β = 0.016 and at 50 seconds for β = 0.032 to β = 0.065.

Five replications of the load history were made at six packing ratios from 0.004 to 0.065. Table 1 is a compilation of the maximum load-loss rate, $\dot{w}$, obtained from the burning basket. Table 2 contains Rothermel's original data for excelsior from horizontal spreading fires. Both sets of data are displayed in figure 4 along with a prediction of $\dot{w}$ according to Rothermel (1972) (appendix B). The prediction differs from the original excelsior data because the results of other fuel sizes were amalgamated by Rothermel to obtain the generalized expression for reaction velocity and thus the maximum load-loss rate.

Table 1.--*Maximum load-loss rate of a burning basket of excelsior at different packing ratios*

Packing ratio	Moisture content fraction of ovendry weight	Maximum load-loss rate
		g/cm^2-s
0.004	0.05	2.82 $\times 10^{-3}$
		2.82
		2.49
		2.52
		2.60
.008	.05	4.24 $\times 10^{-3}$
		3.51
		4.02
		4.47
		4.30
.016	.05	4.87 $\times 10^{-3}$
		6.11
		6.34
		6.57
		5.44
.032	.05	6.48 $\times 10^{-3}$
		6.42
		6.20
		6.25
		6.82
.065	.05	3.04 $\times 10^{-3}$
		3.83
		3.16
		3.49
		2.93

Table 2.--*Maximum load-loss rate of a weighed slice of a horizontally spreading fire in excelsior fuel**

Packing ratio	Moisture content fraction of ovendry weight	Maximum load-loss rate
		g/cm^2-s
0.005	0.053	1.84 $\times 10^{-3}$
	.047	2.34
	.056	2.16
.01	.048	4.24 $\times 10^{-3}$
	.045	2.91
	.045	2.89
.02	.052	9.08 $\times 10^{-3}$
	.039	8.40
	.066	4.43
	.050	4.25
	.063	7.64
.03	.054	6.71 $\times 10^{-3}$
	.053	5.52
	.050	5.85
.04	.059	4.29 $\times 10^{-3}$
	.062	4.73
	.054	4.37
.05	.056	4.78 $\times 10^{-3}$
	.056	3.81
	.058	5.48
.06	.058	4.28 $\times 10^{-3}$
	.054	3.32
	.056	3.08

*Data from Rothermel, on file at the Northern Forest Fire Laboratory.

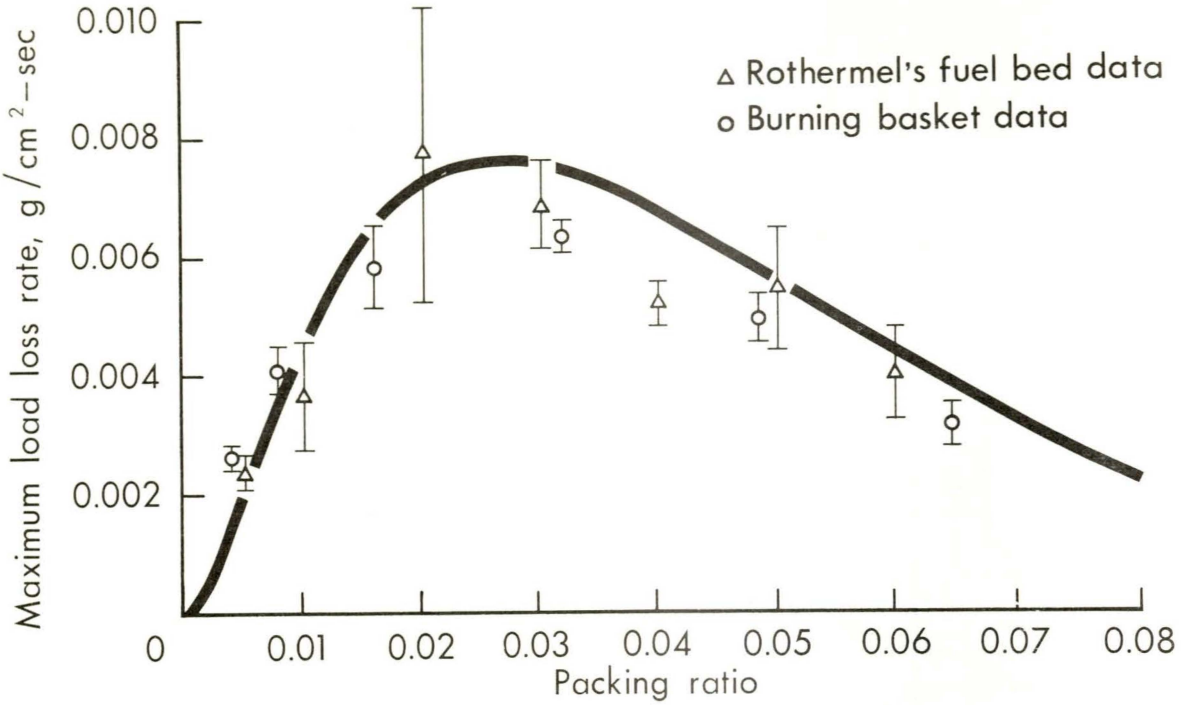

Figure 4.--A plot of the maximum load-loss rate, $\dot{w}$, versus the packing ratio, β, for excelsior burned in a basket and in a fuel bed. The continuous curve was obtained from the expression for $\dot{w}$ in appendix A. The upper and lower extreme are the standard deviation from the mean.

DISCUSSION

The data contained in tables 1 and 2 for the two different methods of obtaining the maximum load-loss rate do not lend themselves to a simple comparison at the same packing ratios. However, assuming that a quadratic model fits these data, we can approximate each data set with a quadratic regression curve, $\dot{w}$ regressed on β, and compare these curves to a quadratic regression of the composite of both data sets. The composite curve expresses fuel loss rate as accurately as the individual data sets if the composite curve has a sum of squared errors (SSE) (squared differences between observed and predicted from quadratic model) not significantly greater than the sum of SSE's from the separate curves. It then follows that the curves are not dissimilar. A statistical test of the data from tables 1 and 2 (appendix C) shows that it is very unlikely that the two data sets are different.

The early load history (fig. 3) of the burning fuel follows a declining sigmoid curve. Shape of the curve varies with packing ratio and is distinguished from other curves through the maximum load-loss rate occurring at the inflection. It is important to determine if the depth was sufficient to achieve the characteristic maximum load-loss rate for each packing ratio. Fuel consumption efficiency is a means of examining this

question. It is indicated in figure 3 at the end of the curve and in the region of increasing slope (second knee except at $\beta = 0.65$) following the inflection of the initial sigmoid curve. For $\beta = 0.032$ to $\beta = 0.065$, 39 to 79 percent of the fuel still remains at 50 seconds--well after the initial sigmoid load history. Consequently, the depth, 15.2 cm, was sufficient for $\beta = 0.032$ to $\beta = 0.065$. For $\beta = 0.004$ to $\beta = 0.016$, as little as 4 percent of the fuel remains at 30 seconds; however, each curve is sigmoid and shows at least 17 percent more fuel consumed beyond the second knee, indicating that the initial sigmoid curve was not foreshortened by lack of fuel depth.

In the spreading fire, the major rate of fuel consumption is near the front of the combustion zone--consistent with its early occurrence in the fuel basket--and is of prime importance to the propagation of the fire (Frandsen and Rothermel 1972).

Converting an idealized load history to load-loss history provides us with an easy reference for comparing the dynamics of burning fuel baskets of constant β having different depths (initial loads). Because the fuel below the pyrolysis zone has no effect upon the present load-loss history, we can see that the load-loss curve for an extreme depth will have all the characteristics of load-loss curves of lesser depth (fig. 5), except that the period of constant load-loss rate becomes longer. The slope of the curves in figure 5 to the right of the second knee is dependent on char buildup. Char formation depends on the mineral content of the fuel and increases with oxygen depletion that in turn increases with time as the pyrolysis zone travels down into the basket. The char buildup for excelsior is negligible up to and including the maximum load-loss rate because the maximum rate occurs early in the load history and the mineral content is low (0.03 percent). Whatever the effect, it is the same for both the slice and the basket.

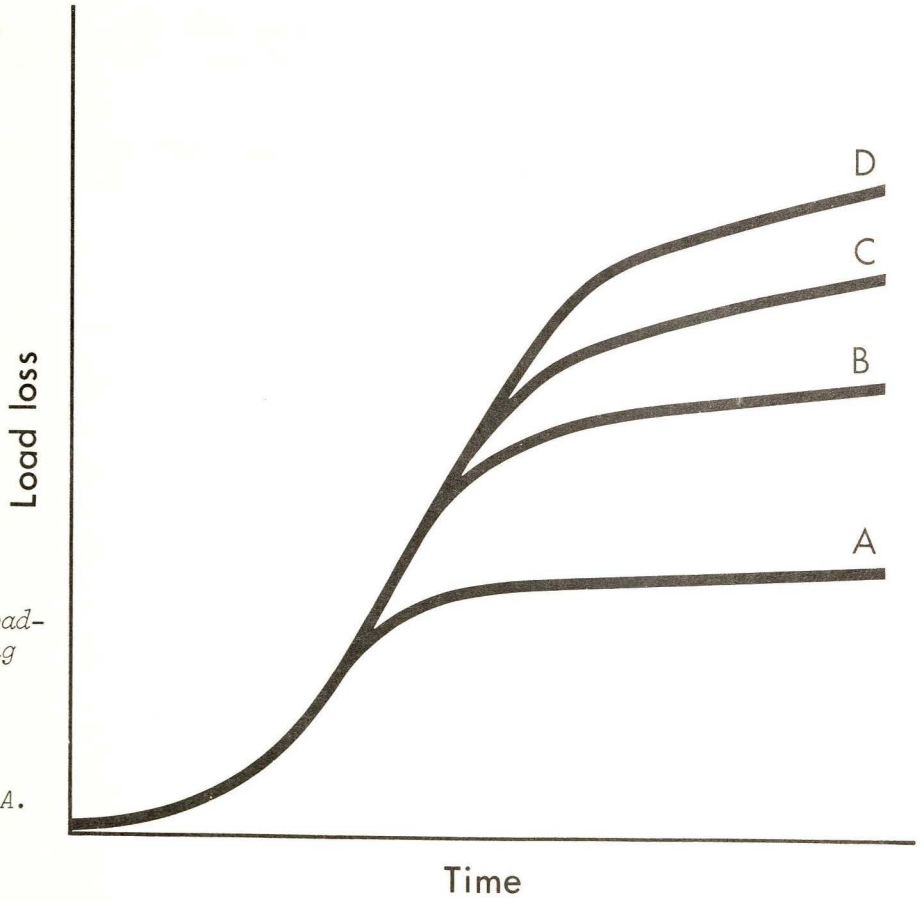

Figure 5.--An idealized load-loss history of a burning fuel basket of extreme depth, curve D, having similar characteristics to a basket of lesser depth, curves C down to A.

The statistical test in appendix C indicates that the alternative method presented here can be used for fuel near the size of excelsior to obtain the reaction velocity used by Rothermel to describe the dynamics of a horizontally spreading fire. Investigations at larger fuel sizes are necessary to extend the range of the usefulness of this method.

This method should be useful in studying fire spread in forest fuels comparable in size to excelsior. Some specific applications that come to mind are; dependence of fire spread on natural variables such as mineral content, moisture content, extractive content, and packing ratio, and also the efficacy of fire-retarding chemicals.

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APPENDIX

Appendix A

Terms

SYMBOL		DEFINITION	UNIT
$\dot{w}$	=	Maximum load-loss rate	g/cm^2-s
w_n	=	Net original ovendry load (less inorganics)	g/cm^2
Γ	=	Reaction velocity	s^{-1}
Γ'	=	Optimum reaction velocity	s^{-1}
Γ'_{max}	=	Maximum optimum reaction velocity	s^{-1}
h	=	Low heat content of fuel	cal/g
I_R	=	Reaction intensity	cal/cm^2-s
δ	=	Fuel depth	cm
σ	=	Surface area-to-volume ratio	cm^{-1}
β	=	Packing ratio, the fraction of bulk volume occupied by fuel	cm^3/cm^3
β_{op}	=	Optimum packing ratio	cm^3/cm^3
ρ_p	=	Ovendry particle density	g/cm^3
η_s	=	Mineral damping coefficient	
η_m	=	Moisture damping coefficient	
S_e	=	Silica free ash content	Fraction of ovendry weight
M_f	=	Fuel moisture content	

Appendix B

Derivation of Maximum Load-Loss Rate

Beginning with $\dot{w} = w_n \Gamma$, the net load is expressed as

$$w_n = \rho_p \beta \delta$$

where

ρ_p = ovendry particle density

δ = depth of the fuel basket or fuel slice

β = packing ratio, the fraction of the bulk volume occupied by fuel.

The other term in the expression for $\dot{w}$ is the reaction velocity, Γ. Rothermel (1972) provides a set of parametric equations for obtaining Γ from initial fuel parameters.

$$\Gamma = \eta_s \eta_m \Gamma'$$

where

η_s = mineral damping coefficient = f (silica free ash content)

η_m = moisture damping coefficient = f (fuel moisture content)

Γ' = optimum reaction velocity

and

$$\Gamma' = \Gamma'_{max} (\beta/\beta_{op})^A \exp[A(1-\beta/\beta_{op})]$$

$$\Gamma'_{max} = \sigma^{1.5}(495 + 0.0594\ \sigma^{1.5})^{-1}$$

$$\beta_{op} = 3.348\ \sigma^{-0.8189}$$

$$A = 1/(4.774\ \sigma^{-1} - 7.27)$$

σ = particle surface area-to-volume ratio

Substituting w_n and Γ into $\dot{w}$ gives

$$\dot{w} = \rho_p \delta \eta_s \eta_m\ \beta\ \Gamma'$$

From Rothermel's (1972) original data

$\rho_p = 26.12$ lbs/ft^2

$\delta = 0.375$ ft

$\eta_m = 0.694$ @ $M_f = 0.05$

$\eta_s = 0.507$ @ $S_e = 0.0036$

Substituting into $\dot{w}$ we have

$$\dot{w} = 0.0280\ \beta\ \Gamma'$$

with $\sigma = 1{,}848$ ft^{-1} for excelsior

$$\Gamma' = 15.237\ e^{0.3498}\ [\beta'\ e^{-\beta'}]^{0.3498}$$

where

$$\beta' = \beta/0.00707$$

Appendix C

Statistical Test

Statistical test of the similarity between the maximum load-loss rate dependence on packing ratio of the alternative burning basket method and the horizontally spreading fire.

The SSE and degrees of freedom, d.f., are given in the following tabulation. The model assumes a second degree polynomial.

Data set	SSE*	d.f. = n-3
Verticle burn, SSE(V)	9.5600×10^{-6}	27
Horizontal burn, SSE(H)	43.6092×10^{-6}	20
Composite, SSE(C)	58.0511×10^{-6}	50

*Sum of squared errors

Forming F value according to Draper and Smith (1966)

$$F = \frac{(\Delta SSE/\Delta d.f.)}{(SSE(V+H)/d.f.(V+H))}$$

Therefore

$$F = \frac{(4.8819\times10^{-6}/3)}{(53.1692\times10^{-6}/47)} = \frac{(4.8819)(47)}{(53.1692)(3)}$$

$$F = 1.4385$$

Given no difference in the two sets of data the probability of such a value for F, is 0.24. Therefore, we accept the hypothesis that both methods are estimating the same result.

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1978. Fuel burning rates of downward vs. horizontally spreading fires. USDA For. Serv. Res. Pap. INT-214, 12 p. Intermt. For. and Range Exp. Stn., Ogden, Utah 84401.

Describes a vertical, cylindrical fuel array that requires less fuel and less time to set up and to measure combustion rates than the flat fuel arrays used previously in laboratory studies of fire. Rates of combustion were comparable in horizontally and vertically (downward) spreading experimental fires.

KEYWORDS: fire spread, excelsior fuel, burning rate, load-loss rate, fire behavior.

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